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A possible redshift evolution of the time-lag and variability luminosity relations for long gamma-ray bursts

W.J. Azzam [a,*], M.J. Alothman [a], N. Guessoum [b]

[a] Department of Physics, College of Science, University of Bahrain, Sakhir, Southern Governate 32038, Bahrain
[b] Department of Physics, American University of Sharjah, United Arab Emirates

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Abstract

Several luminosity relations currently exist for long gamma-ray bursts (GRBs). Some were derived from the light curves; others were obtained from the spectra. In this study, we consider two of these luminosity relations: the time-lag, τ_{lag}, relation and the variability, V, relation and investigate their possible dependence on (or "evolution" with) the redshift, z.

The data we use are taken from Schaefer's literature (Schaefer et al., 2007) in which 69 long gamma-ray bursts were analyzed. The method consists of binning the data by redshift interval, then writing the time-lag relation in the form $\log(L) = A + B\log[\tau_{lag}/(1+z)]$ and extracting the fit parameters A and B for each redshift bin; likewise, for the variability relation, which we write in the form $\log(L) = A + B\log[V(1+z)]$. The objective is then to see whether the fitting parameters A and B evolve in any systematic way with the redshift. Our analysis indicates that both the A and B parameters do evolve with z in a systematic way for the lag-relation but not for the variability relation. A flat universe with $\Omega_M = 0.3, \Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1} is assumed.

Keywords: Gamma-ray bursts; Luminosity relations; Evolution

1. Introduction

In recent years several GRB luminosity indicators have been proposed. Some, like the lag-relation (Norris et al., 2000) and the variability relation (Fenimore and Ramirez-Ruiz, 2000), are based on light curves and thus require a large number of counts. Others are based on spectra and include (among others) the Amati relation (Amati et al., 2002; Amati, 2006), the Ghirlanda relation (Ghirlanda et al., 2004), the Yonetoku relation (Yonetoku et al., 2004), and the Liang–Zhang relation (Liang and Zhang, 2005).

The importance of these relations lies in their potential use as cosmological probes. Several studies have been done to constrain cosmological parameters, such as Ω_M and Ω_Λ, by utilizing the above relations (Ghirlanda et al., 2006; Capozziello and Izzo, 2008; Amati et al., 2008). For these reasons and more, several generalized tests have been carried out to check the robustness of these relations (Schaefer and Collazi, 2007) and in fact to produce a GRB Hubble diagram (Schaefer, 2007). On the other hand, some studies have tried to deal with the problems of circularity and selection effects inherent in these schemes (Li et al., 2008; Butler et al., 2008; Ghirlanda et al., 2008; Nava et al., 2009).

On the other hand, less attention has been given to the possible redshift evolution of these luminosity relations, that is, to the possible dependence of the calibration coefficients that appear in these relations on redshift, as evidenced by the few studies that have been dedicated to this issue (Li, 2007; Tsutsui et al., 2008). However, given that these relations are typically calibrated using a GRB sample that spans a wide range in redshift (typically $0.1 \leqslant z \leqslant 6$), it becomes essential to investigate whether these relations evolve with redshift, especially if GRBs

* Corresponding author. Tel.: +973 39446804; fax: +973 17449148.
E-mail addresses: wjazzam@sci.uob.bh (W.J. Azzam), malothman@sci.uob.bh (M.J. Alothman), nguessoum@aus.edu (N. Guessoum).

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are to be used as "standard candles" to probe cosmological models. The purpose of this paper is then to look at the possible redshift-dependence of some of these relations, specifically the lag-relation and the variability relation, and hence to assess how robust and reliable they can be as cosmological probes.

In this study, we consider two of these luminosity relations: the time-lag, τ_{lag}, relation and the variability, V, relation and investigate their possible dependence on (or evolution with) the redshift. Our analysis and results are presented in Section 2, which is followed by a discussion in Section 3, and our conclusions are provided in Section 4. A flat universe with $\Omega_M = 0.3, \Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1} is assumed.

2. Analysis and results

The data we use consist of 69 long GRBs that were taken from Schaefer (2007), who used these bursts to study and calibrate six luminosity relations and then to create a Hubble diagram. It is worth mentioning that although Schaefer (2007) states that these luminosity relations are not expected to evolve with redshift, the arguments he presented were based on the consideration of the physical mechanisms behind these luminosity relations rather than on a detailed data analysis that specifically addresses the issue of redshift evolution. Indeed, the focus of the Schaefer (2007) paper was not the redshift evolution of the luminosity relations.

In this paper, we specifically focus on the possible redshift evolution of two luminosity relations: the lag-relation, L versus τ_{lag}, and the variability relation, L versus V, where L is the isotropic luminosity which we calculate using

$$L = 4\pi d_L^2 P_{bolo}, \tag{1}$$

where P_{bolo} is the bolometric peak flux (in erg s^{-1} cm^{-2}), and d_L is the luminosity distance (in cm), which we determine by assuming a flat universe with $\Omega_M = 0.3, \Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}.

The time-lag, τ_{lag}, is the time shift between the light curves of soft and hard photons, with the hard photons arriving a little earlier. More specifically, the time-lag was originally defined by Norris et al. (2000) for 7 BATSE bursts (6 of which had redshifts) as the delay in the time of peaks in the 25–50 and 100–300 keV energy bands. Since the data sample we analyze comes not only from the BATSE instrument but also from HETE-2, Swift, and Konus, there is a need to specify the "soft" and "hard" energy channels for each of them in order to determine the time-lag. Following Schaefer (2007), we consider the time delay for the Swift data as that corresponding to the energy channels 25–50 and 100–350 keV, and for the HETE-2 data as that corresponding to the energy channels 7–40 and 30–400 keV. Since Konus has only one energy channel, no τ_{lag} could be defined. Several theoretical explanations have been proposed to understand the astrophysical origin of the lag-relation (Ryde and Svensson, 2002; Schaefer, 2004; Dado et al., 2007). The basic idea is that the inverse proportionality between L and τ_{lag} is a reflection of the fact that the shocked material cools off at a rate set by L, and that τ_{lag} is related to the cooling time. Hence, a luminous burst would cool off fast and so would have a short τ_{lag}.

The variability, V, is basically a measure of how spiky a GRB's light curve is. Unfortunately, quantifying this measure is not easy, and different approaches (Fenimore and Ramirez-Ruiz, 2000; Reichart et al., 2001; Schaefer et al., 2001) have not always yielded the same values. In our analysis we follow the definition of Schaefer (2007), since our data sample is taken from that paper. There have been several attempts to explain the astrophysical origin of the variability relation (Mészáros et al., 2002; Kobayashi et al., 2002). Basically, in models dealing with relativistically shocked jets, both L and V depend on the jet's bulk Lorentz factor, Γ. The luminosity scales with Γ to some power; and high values of Γ lead to visible emission from smaller regions with relatively short pulse durations and fast rise times and hence a higher V.

The entire data sample consists of 69 GRBs, of which 38 have τ_{lag} values and 51 have V values. Note that Schaefer (2007) identified six outlier bursts, four of which (GRB 980425; GRB 020819; GRB 031203; GRB 050315) have been completely excluded from his and our analysis since they are clear outliers as far as the luminosity relations are concerned. The other two (GRB 990123; GRB 030328) we have kept since they have a problem only with their rise time, τ_{RT}, but not with their time-lag or variability. The method consists of binning the data by redshift, z, then writing the time-lag relation in the form:

$$\log(L) = A + B\log[\tau_{lag}/(1+z)] \tag{2}$$

and extracting the fit parameters A and B for each redshift bin; likewise, for the variability relation, which we write in the form:

$$\log(L) = A + B\log[V(1+z)]. \tag{3}$$

The objective is then to see whether the fitting parameters A and B evolve in any systematic way with the redshift.

The binning was done in two ways for each of the two relations. In the first approach, the binning was done by number in which the number of bursts per bin was fixed. For instance, for the lag-relation: all 38 bursts at once in the first instance; two bins of 19 each (with, respectively, lesser and greater redshifts); three bins of 13, 13, and 12 by increasing values of redshifts. In the second approach, the binning was done by width in which the Δz was fixed, and here only 36 bursts for the lag-relation could be utilized (instead of the available 38) since 2 bursts had redshifts greater than 4 and so would have formed a bin by themselves, and for the same reason only 50 bursts (out of the available 51) were utilized for the variability relation. Note that going for more bins is constrained by statistics, given the paucity of data points.

The results for the lag-relation are shown in Table 1, where r is the linear regression coefficient for the best-fits, which were obtained using a least-squares method. The errors in A and B are 1σ errors, and to show the goodness